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Modeling Flow through a Lock Manifold Port

by Richard L. Stockstill and E. Allen Hammack

BACKGROUND: Manifolds are essential components of a navigation lock's filling and emptying system. They are used as intakes, outlets, and lock chamber filling and emptying culverts. Evaluation of a lock system requires an understanding of the hydraulics of manifolds. Analytical solutions of lock manifold flow are given by Stockstill et al. (1991), Allen and Albinson (1955), Webster et al. (1946), Soucek and Zelnick (1945), and Zelnick (1941). One-dimensional (1-D) numerical flow solvers such as LOCKSIM (Schohl 1999) are also used to calculate the flow and pressures in lock manifolds. Each of these evaluation techniques requires knowledge of energy loss coefficients for multi-ported manifolds.

Hydraulic coefficients for industrial manifolds which have common geometries such as tees and wyes are readily available in the literature (e.g. Miller 1990). However, the culvert and port shapes and sizes in lock manifolds are very different from typical industrial manifolds and vary from project to project. These structural differences make generalizing the solution of velocity and pressure distribution in lock manifolds impossible. Hydraulic coefficients for a limited number of port shapes have been determined from laboratory experiments using single-port models. Examples of single-port laboratory data are provided by Zelnick (1941) and Webster et al. (1946).

Construction and testing of a laboratory model can be expensive. An economical alternative would be the use of a three-dimensional (3-D) computational flow model. This technical note describes the use of a detailed 3-D computational flow model to determine the velocity and pressure distribution in a single-port manifold for a range of port-to-culvert discharge ratios. The flow solutions are then used to calculate energy losses in flow exiting a manifold port. Finally, this energy loss information is presented in terms of head loss coefficients required for a 1-D flow analysis of a multi-ported manifold.

This technical note documents the validity of using a 3-D computational flow model to obtain loss coefficient information required for manifold flow analysis. The modeling process is validated by comparing computational results with previously published laboratory data.

HYDRAULICS OF LOCK FILLING AND EMPTYING MANIFOLDS: Lock chamber manifolds are used to provide an even rate of filling or emptying throughout the lock chamber. An even rate of filling or emptying is necessary to ensure safe navigation within the lock chamber during lock operations. Various filling and emptying manifold systems such as the sidewall port, bottom longitudinal (H-system and H-H-system), and bottom lateral (split and interlaced) are designed to provide even flow distribution into lock chambers. The most recently developed system is referred to as the In-chamber Longitudinal Culvert System (ILCS, Hite and Stockstill 2004). This system was used in the designs of the newly constructed McAlpine and Marmet Locks.

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Details of the ILCS design are found in EM 1110-2-1604 (Headquarters, US Army Corps of Engineers 2006).

Navigation lock manifolds can be evaluated using analytical methods when the hydraulic characteristics associated with the manifold's geometry are known. The solution method uses a series of energy equations expressed for the fluid path through each port (Stockstill et al. 1991). The equations consider energy losses due to the culvert boundary friction, the energy loss in flow through a port, and the energy loss in culvert flow across a port. These energy losses are calculated using loss coefficients. The energy loss coefficient for flow passing through a port (K) is defined as the ratio of head loss to velocity head:

$$K = \frac{H_L}{V^2/2g}$$

where

H_L = head loss in flow through the port,
V = average velocity in the culvert upstream of the port, and
g = acceleration due to gravity.

Laboratory experiments. A lock port testing facility was constructed in support of innovative lock design research. This facility (Figure 1) was used to quantify hydraulic loss coefficients for a generalized ILCS port shape. This port design, shown in Figure 2, has been used with the ILCS (Hite and Stockstill 2004, Hite 2003) on innovative lock designs such as the new McAlpine Lock, Ohio River (Hite 2000 and Stockstill 1998) and the new Marmet Lock, Kanawha River (Hite 1999).

The single-port testing facility was a hydraulic model whose culvert was constructed of acrylic plastic and lock chamber reservoir was made of plastic-coated plywood. The culvert was 25.91-cm-wide by 29.51-cm-tall. The facility had 7.0 m of straight culvert upstream of the port and 2.0 m of straight culvert downstream. There were two ports, one on either wall, at the ported station as illustrated in Figure 2. Each port was 2.38-cm-wide by 5.49-cm-tall and was located at the mid-height of the 5.12-cm-thick culvert walls. Each port edge was rounded with a 2.57 cm radius. The lock chamber reservoir was 1.52-m-wide by 2.35-m-long by 0.80-m-tall. The port discharge (Q_3) flowed into the lock chamber reservoir which in turn emptied into a 10-cm-wide by 20-cm-tall channel where the flow passed over a V-notched weir for measurement. The outflow from the downstream end of the culvert (Q_2) was also measured using a V-notched weir. Continuity was used to calculate the total flow entering the upstream end of the culvert (Q_1). The port-to-culvert discharge ratio (Q_3/Q_1) was varied by adjusting a vertical slide gate located at the downstream end of the culvert.

Pressures within the culvert were measured using piezometers located along the culvert floor as illustrated in Figure 1. The water-surface elevation of the reservoir was measured with a point gage. The pressures and discharges were documented for 30 flow configurations, wherein the port-to-culvert discharge ratio ranged from 0.06 to 0.99. These data provided pressure variations along the culvert and variations between the culvert and the reservoir. The piezometric grade line was developed from the pressure data. The pair of ports was treated as a single loss component. The discharges were used to calculate the average velocities in the culvert and in the port.

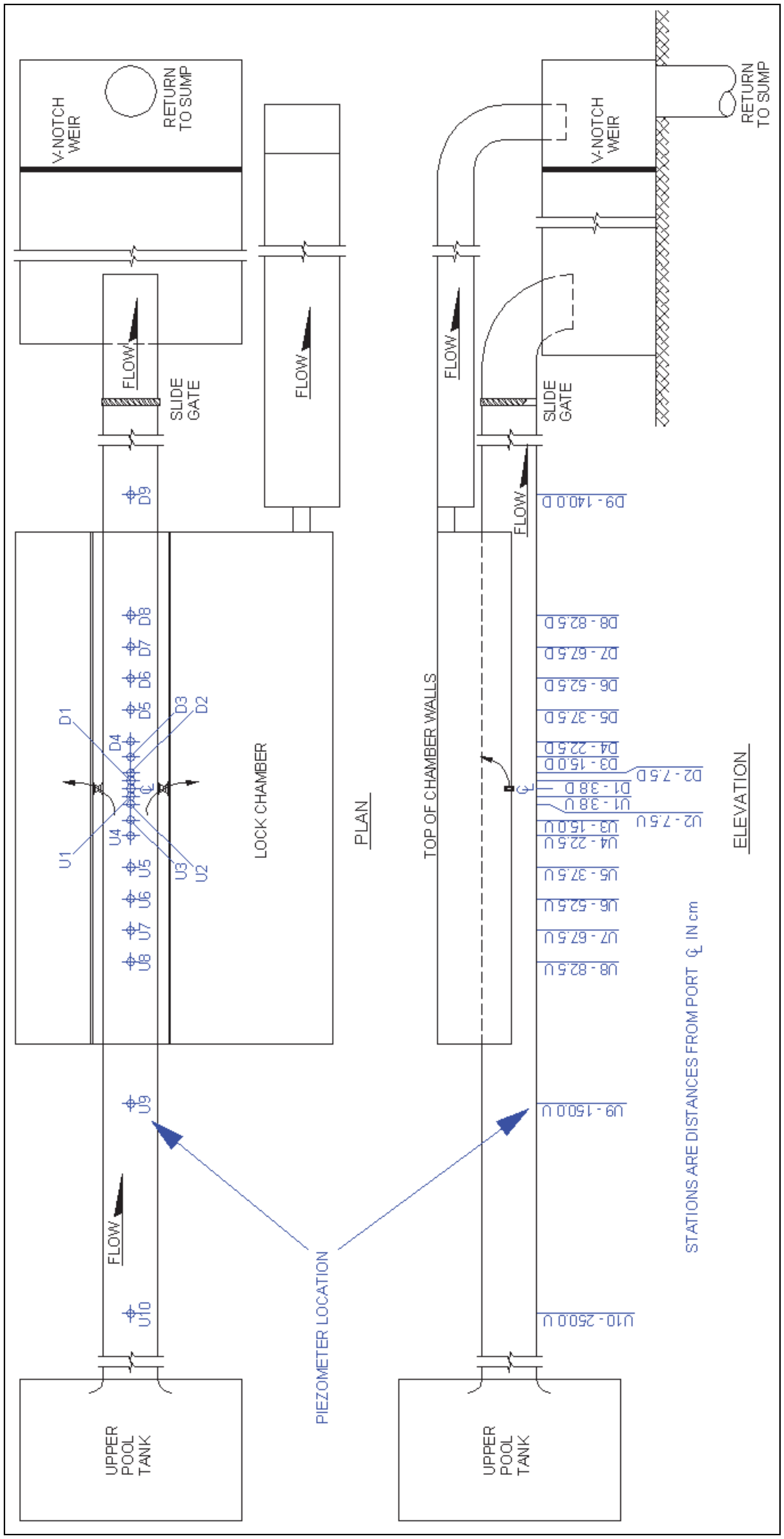

Figure 1. Layout of port testing facility and piezometer locations.

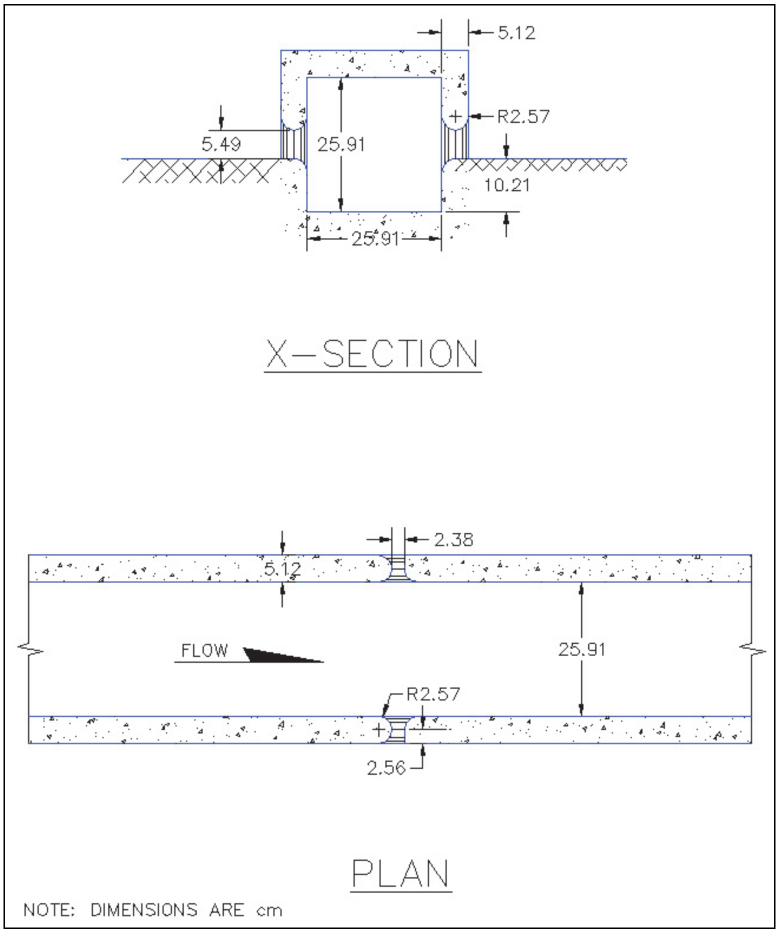

Figure 2. Details of ILCS port model.

The velocity heads, calculated using the average velocities, were added to the piezometric grade line to form the energy grade lines upstream and downstream of the port. In the lock chamber reservoir, the velocity head was negligible so the water-surface elevation was taken as the energy grade line. This energy information allowed the losses through the system to be calculated.

Computational model. Tests were conducted to determine the flow model's ability to reproduce the energy losses in flow through a geometrically complicated manifold. A computational model consists of the governing equations, the discretization scheme used to numerically solve the equations, the computational mesh on which the domain is discretized, and the boundary and initial conditions needed to close the system of equations. The 3-D Reynolds-Averaged Navier-Stokes (RANS) equations are used to model the flow in lock components such as manifolds. The commercial code ANSYS Fluent (*www.ansys.com*) provided solutions to the RANS equations. Discretization of the flow domain began with a CAD representation of the flow boundaries including the culvert, port, and reservoir representing the lock chamber. Pictures of the 3-D CAD model are presented in Figure 3. The computational model was a replica of the laboratory port testing facility in that the culvert was 25.91-cm-wide by 29.51-cm-tall and the ports were 2.38-cm-wide by 5.49-cm-tall. A computational mesh having 398,428 tetrahedral elements and 77,158 nodes was constructed to fill the volume defined by the CAD model.

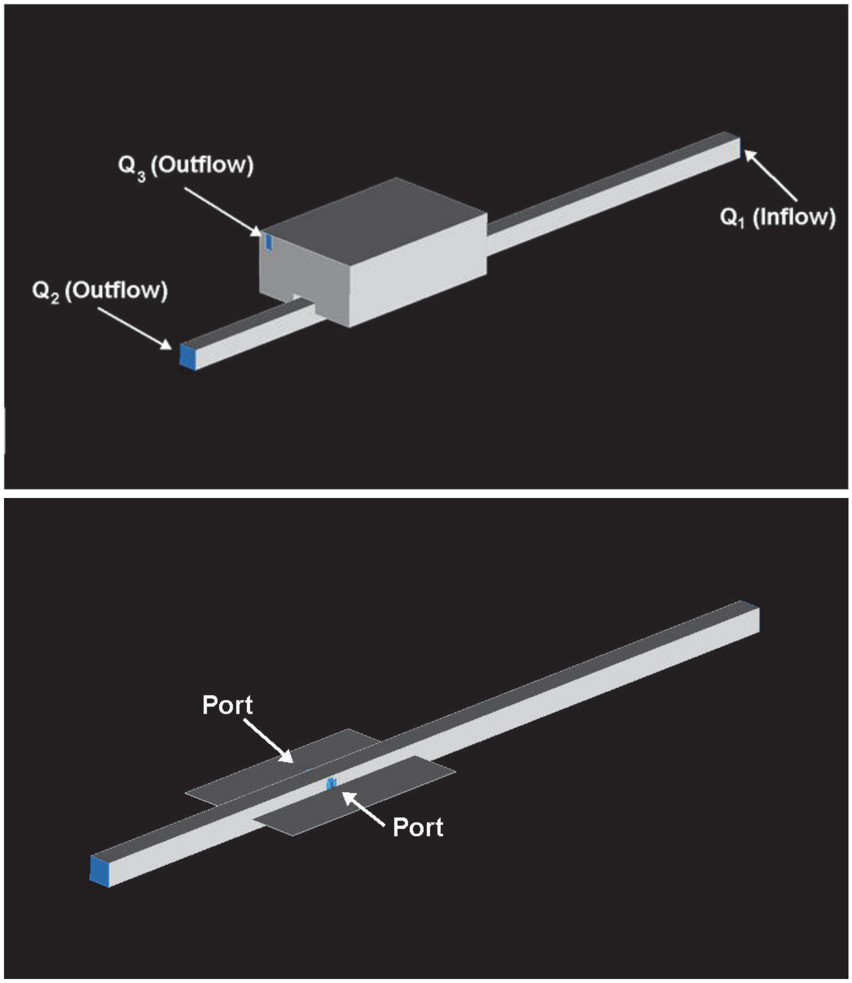

Figure 3. CAD model of port testing facility.

Element side lengths ranged from about 3.5 cm at the culvert center to less than 0.3 cm near the port. Element size variation is illustrated by the pictures of the computational mesh provided in Figure 4. The first picture shows the surface mesh of the manifold culvert and a port. The surface mesh is the set of faces of the tetrahedral elements that form the model's boundary. The two other pictures show the tetrahedral elements along a slice through the center of the port. The slice is normal to the longitudinal axis of the culvert. The mesh was particularly fine in the vicinity of the ports.

Flow entered the model at the culvert's upstream end, was split at the two ports, and the remainder exited the culvert's downstream end. The flow that passed through the ports eventually exited the model through the lock chamber reservoir outlet. The discharge through two of the model's three flux boundaries was specified in terms of velocity normal to the flux boundary. Inflow and reservoir outflow velocities were specified, which in turn set the port-to-culvert discharge ratio. The boundary conditions were set so that the resulting Reynolds numbers would be the same order of magnitude as those of the laboratory experiments. The Reynolds number in the culvert upstream of the port was chosen to be 100,000, which equates to an inflow velocity of 0.387 m/sec. The culvert and reservoir walls were treated as no flux boundaries.

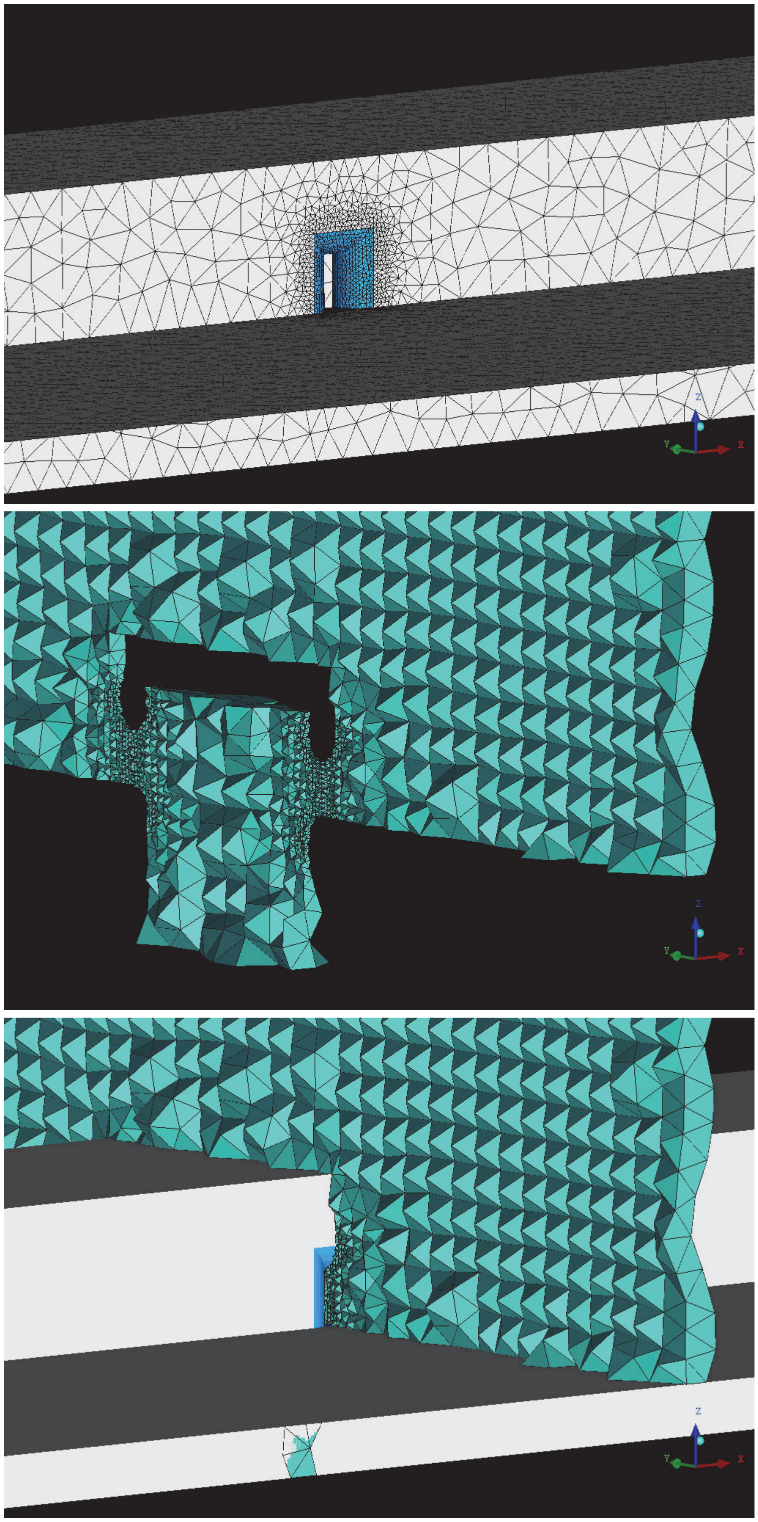

Figure 4. Computational mesh of port testing facility.

Energy losses must be calculated accurately if the computational model is to provide reliable loss coefficients. Energy losses for flow issuing from a port occur primarily in the submerged jet. The computational model must include a turbulence closure model that is appropriate for the problem. The choice of turbulence model is not straightforward since the jet experiences free shear but is also partially wall-bounded. The jet expands as it moves along the lock chamber floor and then meets the chamber wall. Two popular, two-equation turbulence closure models, the *k*-ε and the *k*-ω models (see Wilcox 2006), were tested.

Nine port-to-culvert discharge ratios, varying from 0.1 to 0.9, were simulated. Each flow configuration was modeled using the *k*-ε and the *k*-ω models. Typical computational model results are shown on the velocity contour plot in Figure 5. The velocity distribution illustrated in Figure 5 is the result of a port-to-culvert discharge ratio of 0.5 using the *k*-ω model.

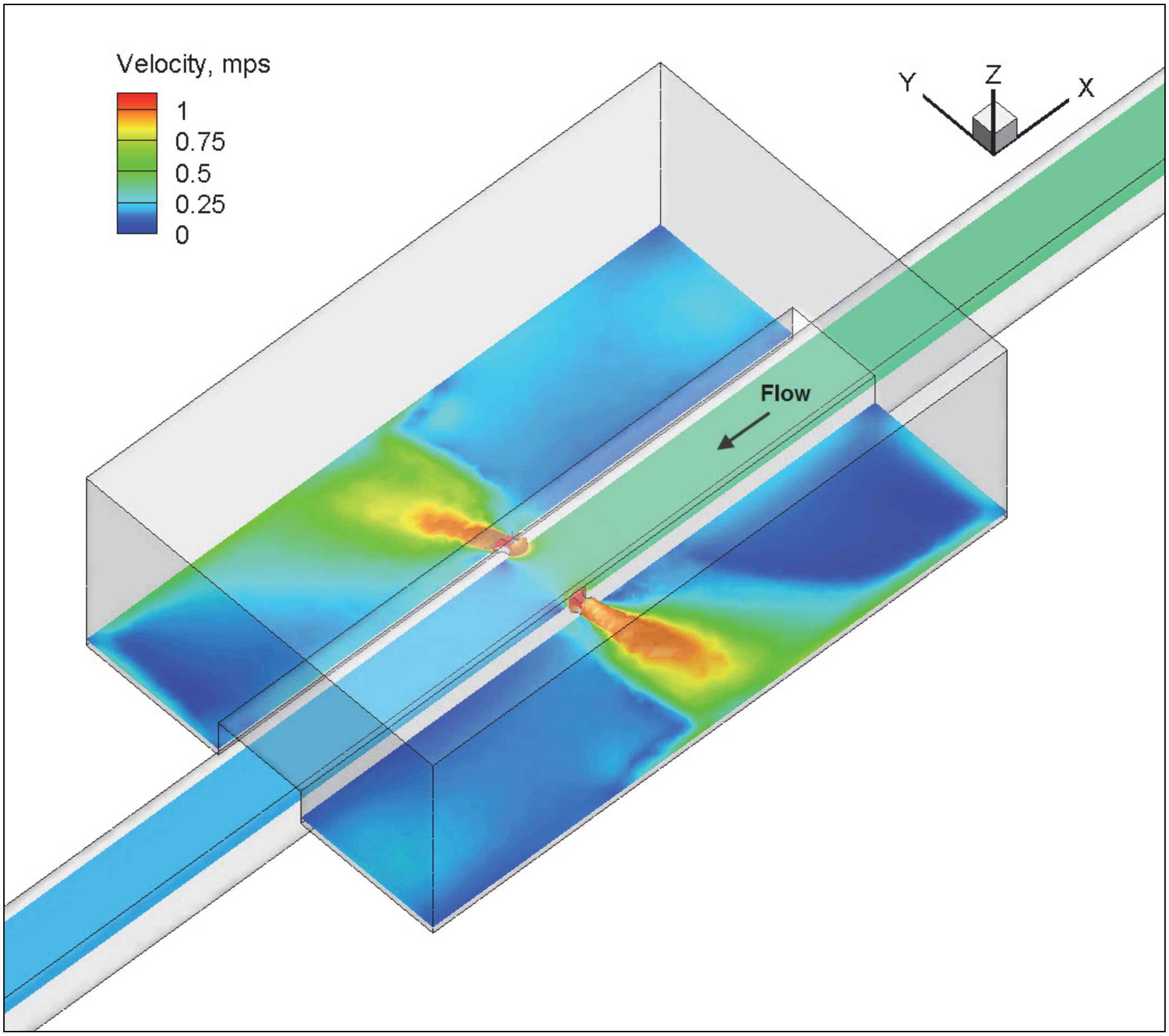

Figure 5. Computational model of port testing facility, velocity contours on a horizontal plane passing through the ports, Q_3/Q_1 = 0.5.

RESULTS:

The computed results and observed data are compared on the plot of energy loss coefficient for flow through the port shown in Figure 6. The loss coefficient is presented as a function of the port-to-culvert discharge ratio (Q_3/Q_1).

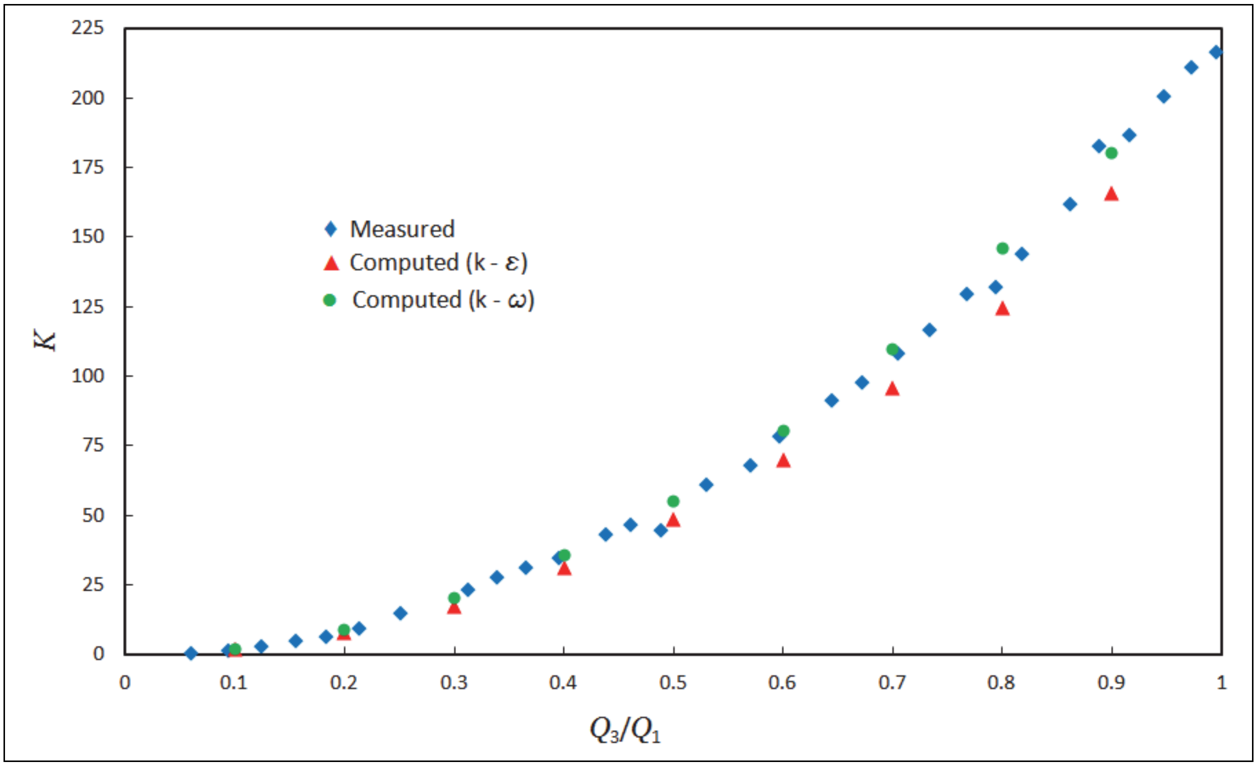

Figure 6. Comparison of laboratory data and computational model results.

The observed loss coefficients are data from a series of thirty flow conditions that were documented in the laboratory model. The computational results such as those pictured in Figure 5, provided a single point on the loss coefficient plot in Figure 6.

The *k*-ω results are nearly identical to the laboratory data. The *k*-ε model tended to under-predict energy losses although the largest difference is only about eight percent. No general conclusions can be drawn regarding the two turbulence models in applications to modeling flow issuing from a single manifold port. Other port and culvert shapes would have to be modeled before a conclusion can be drawn as to whether the *k*-ε or the *k*-ω model is more accurate in predicting energy losses in port flow. One speculation is that either turbulence model would provide sufficiently accurate results. The plot (Figure 6) shows that the numerical model is capable of providing energy loss coefficients for flow through a lock manifold port.

CONCLUSIONS:

This technical note shows that a 3-D detailed computational flow model can be used in a manner similar to a physical model to determine the energy loss coefficients for flow through a manifold port.

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ACRONYMS AND ABBREVIATIONS

Term	**Definition**
1-D	One-dimensional
3-D	Three-dimensional
ANSYS	ANalysis SYStem software
CAD	Computer Aided Design
CHETN	Coastal and Hydraulics Engineering Technical Note
cm	Centimeters
EM	Engineering Manual
g	The acceleration due to gravity
H_L	The head loss in flow through the port
H-System	A bottom longitudinal floor culvert system
H-H System	A bottom longitudinal floor culvert system
ILCS	In-chamber Longitudinal Culvert System
K	The head loss coefficient for flow through the port
k-ε	k-ε Two-equation turbulence closure model
k-ω	k-ω Two-equation turbulence closure model
LOCKSIM	The LOCK SIMulator numerical flow solver software package
m	Meters
m/sec	Meters per second
Q_1	The total discharge entering the upstream end of the culvert
Q_2	The discharge exiting the downstream end of the culvert
Q_3	The discharge through the port
RANS	Reynolds-Averaged Navier-Stokes
sec	Seconds
V	The average velocity in the culvert upstream of the port